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PROSPECTS FOR TOOLS WITH CERAMIC CUTTING PLATES IN MODERN METAL WORKING

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The trends in further expansion of the applications of tools with ceramic cutting plates in modern metal working are shown. An algorithm developed for controlling the operational indicators of ceramic cutting plates that is oriented toward making plates for prescribed operating conditions is presented. Equipping this algorithm with new methods and technologies should encourage commercial enterprises to make wider use of tools with ceramic cutting plates in metal working.

Key words: tools with ceramic plates, wear, failure, operation model, operation defects, stress, algorithm for controlling operational indicators.

One growth trend in modern metal working is efficient use of high-speed cutting, capable of substantially increasing production capacity and accuracy [1]. High-speed cutting under extreme operating conditions of all elements of a technological system creates special requirements for their functional and operational properties.

The requirements introduce by high-speed cutting are taken into account fully in the development of promising machine-tool systems. Metal-cutting machine tools are equipped with spindle assemblies, developing speeds to 100,000 rpm, and feeding mechanisms, which can generate auxiliary velocities to 100 m/min. For the main spindle, high rotational accuracy is attained by using aero- and hydrostatic supports as well as direct drive on blanks and tools. Metal-cutting machine tools have improved dynamic characteristics. These tools are equipped with systems that correct for the thermal deformation of a spindle and limit the play of a spindle to 10 – 50 nm [2]. To compensate the systematic and random errors, machine tools are equipped with sensors in the size-adjustment control systems, making high positioning accuracy possible.

The technological capabilities of metal-cutting machine tools are considerably expanded by highly concentrating the operations which are performed (turning, boring, milling, and drilling). Modern control systems make it possible to set the optimal cutting regimes and the tool trajectory. A new generation of tools capable of adapting to the operating conditions has been developed [3]. The new-generation tool systems will make it possible to perform high-speed tooling changes automatically, perform state diagnostics, and check tool stability. Machine tools are equipped with high-capacity systems for removing chips and feeding lubricant and coolant into the work zone.

However, the practical use of this powerful technological potential, geared toward high-speed cutting, is limited by the capability of the cutting tools to resist wear and failure occurring in intense operating regimes. This focuses researchers' attention on developing tools made of new-generation materials capable of withstanding extremely high thermal and force loads during operation. High-density ceramic materials possessing high hardness and heat resistance are very often considered as a base for solving this problem.

However, tools equipped with modern ceramic cutting plates are not widely used in commercial enterprises, first and foremost, because their reliability is unsatisfactory. For this reason, an obviously contradictory situation has developed — the demand by commercial enterprises for tools with ceramic cutting plates, which can determine the future development of metal working, is too low at the present time.

The objective of the present work is to evaluate the prospects for tools with ceramic cutting plates in modern metal

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TABLE 1. Stages in Improvements to Tool Ceramic

Periods, years	Scientific advances	Material property
1930 – 1950	Development of single-component tool ceramic based on aluminum oxide	Sintered corundum; oxide ceramic with glass phase
1955 – 1975	Development of hardened tool ceramic based on aluminum oxide	Oxide-carbide ceramic; oxide-carbide ceramic with several carbides
1980 – present	Development of tool ceramic based on ceramic materials used in construction	Nitride ceramic; oxide ceramic, reinforced with filamentary silicon carbide crystals

working and to determine on this basis the trend in the development of such tools.

Cutting (tool) ceramic has followed a complicated evolutionary path. This material was first mentioned at the beginning of the twentieth century, while systematic work on the development of ceramic tools appeared in the 1930s [4]. At that time cutting plates made from aluminum oxide without a metal binder (sintered corundum) were manufactured almost simultaneously in the Soviet Union, Germany, and England using technologies from the abrasives and porcelain industry. The subsequent stages in the perfection of tool ceramic are presented in Table 1.

Analysis of historical trends shows that the development of tool ceramic was always geared toward creating a material that is capable of withstanding higher operating temperatures without any changes in strength and hardness. The solution of similar problems in the aerospace science and technology led to the fact that in mid-1980s a new trend appeared in the development of tool steel — it became a by-product of ceramic materials used in construction. For example, silicon nitride based ceramics developed for space purposes were used next for fabricating cutting plates [5].

At the present time tool ceramic is conventionally divided into the following groups: ceramic based on aluminum oxide Al_2O_3 (white ceramic or pure ceramic); Al_2O_3 based ceramic with additions of other refractory compounds, as a rule, TiC (mixed ceramic); Al_2O_3 based ceramic strengthened with filamentary SiC crystals (reinforced ceramic); silicon nitride Si_3N_4 based ceramic (nitrid ceramic); and, coated ceramic. The basic properties of ceramic materials in these groups are presented in Table 2 [6].

TABLE 2. Basic Properties of Ceramic Materials from the Groups

Type of tool ceramic	Hardness HRA	Ultimate bending strength σ_b, MPa	Stress intensity factor K_{1c}, $MPa \cdot m^{1/2}$
Oxide (Al_2O_3)	92 – 94	400 – 800	3.4 – 4.8
Oxide-carbide (Al_2O_3 – TiC)	94 – 96	500 – 900	4.5 – 7.5
Oxide-nitride (Al_2O_3 – TiN)	93 – 95	650 – 750	4.9 – 7.3
Reinforced (Al_2O_3 – SiC_{fc})	92 – 94	500 – 900	6.5 – 9.1
Nitride (Si_3N_4)	92 – 96	500 – 1250	4.3 – 10.3

Tools equipped with ceramic cutting plates make it possible to increase the productivity of mechanical working considerably and to increase the quality of the finished parts while meeting ever increasing ecological requirements. These tools are successfully used in finishing operations in the mechanical working of blanks made of cast irons, hardened steels, non-ferrous alloys, and polymer materials. The potential possibilities of tools with ceramic cutting plates are manifested most strongly during high-speed working of parts from which the volume of the chips removed is substantial.

The greatest technical-economic effect from using tools with ceramic cutting plates obtains at enterprises having a highly sophisticated technological environment. For such enterprises, the time-use structure, which is determined by the time spent on the main and auxiliary operations in the production of parts, plays an important role. Enterprises with a highly sophisticated technological environment have a much shorter auxiliary time spent on fabrication because the production processes are extensively automated. An important problem for these enterprises is to decrease the main time spent on mechanical working of blanks, which is best solved by intensifying the cutting regimes.

For the following reasons tools with ceramic cutting plates are eminently suitable for solving this problem. Efficient use of tools with ceramic cutting plates can decrease considerably the main time and decrease expenditures on mechanical working of parts as compared with tools made from a hard alloy (Fig. 1). For example, the recommended cutting speeds can reach 800 m/min for blanks made from grey irons, 500 m/min for malleable iron, 150 m/min for chilled, and 300 m/min for hardened steels and nickel alloys.

At the next stage commercial enterprises which have decided to make extensive use of tools with ceramic cutting plates in technological processes are faced with the problem of performing a critical analysis of the technologies deployed. This is because the improvement of ceramic cutting plates makes it possible to develop high-productivity, high-precision, blade working during which an intergrain structure and minimal residual stresses are formed in the surface layer of the articles. The absence of charged abrasive grains, burns, and cracks on the surfaces of the parts worked with these tools also makes it possible to evaluate critically the role of abrasive working in technological processes. The reduction of the volumes of "ecologically dirty" technologies by adopting instruments that effectuate high-speed cutting

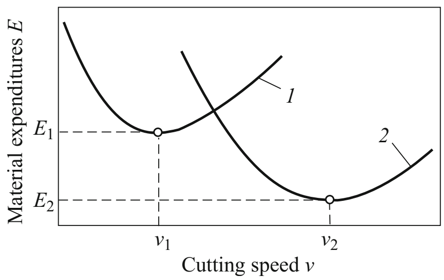

Fig. 1. Expenditures on mechanical working of blanks by tools with cutting plates made from a hard alloy (*1*) and ceramic (*2*).

without lubricant-coolant technological media and satisfying modern ecological requirements makes it possible to decrease the negative effect of industrial production on the environment.

At the same time, in industry the use of tools equipped with ceramic cutting plates is very limited because of the complex of problems presented in a systematized form in Fig. 2.

The use of tools with ceramic cutting plates only at the finishing stages of technological processes, where abrasive working is used conventionally and effectively, cannot greatly affect the general economic performance of enterprises. High-volume feeding during cutting, variable allowances, and modified properties of the surface layer of the blanks — all characteristic for preliminary mechanical working of blanks — create extreme conditions for loading the cutting plates. Brittle blanks do not withstand these loads, which sharply increases the probability of rejection and instability of the operational performance. This is because the failure mechanism for ceramic materials is based on nucleation and propagation of cracks without appreciable plastic deformation. In addition, the conventional mechanisms for stopping cracks in ceramic materials are ineffective for cutting plates because of the extremely high operational loads.

The absence of scientifically substantiated recommendations for designating the cutting regimes, special values, and experience in effectively operating tools with ceramic cutting plates makes production-process engineers less interested in using such tools. This requires changing attitudes at commercial enterprises toward increasing substantially the usage of tools with ceramic cutting plates as being simply a problem of developing a ceramic “with high strength properties.” The problem is complex, and special studies have shown that industrial enterprises await its solution.

Complex studies aimed at solving these interconnected problems are being conducted at the Moscow State Technological University “Stankin.” The complexity of these studies is due to the diversity of the reasons for the failure of ceramic cutting plates and a lack of scientifically substantiated requirements for tool ceramic. It is impossible to change fundamentally the behavior of ceramic cutting plates under the action of high thermomechanical loads only by means of advances in the technology of ceramic materials, on which the

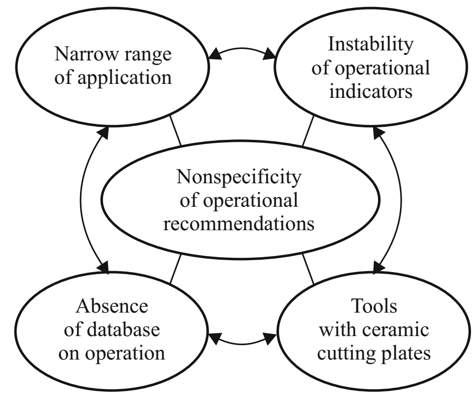

Fig. 2. Reasons for the limited application of ceramic tools with ceramic cutting plates.

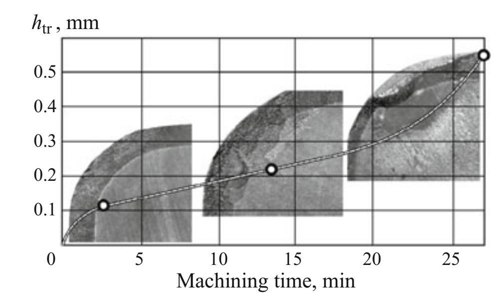

Fig. 3. Effect of the machining time of a blank made of ShKh15 steel on the width h_{tr} of the bevel edge of the trailing surface of a VOK71 ceramic cutting plate (cutting velocity v = 90 m/min, feed rate S = 0.075 mm/rev, cutting depth t = 0.35 mm).

main thrust to solve this problem is being made. The fact that these studies are oriented solely on increasing the strength as well as the crack- and heat-resistance of tool ceramic justifiably raises hopes. In this connection, the research examined here is based on a systems approach to designing, fabricating, and operating tools with ceramic cutting plates.

Studies of the kinetics of the wear of ceramic tools have revealed that wear foci form on the front and back surfaces of ceramic tools (Fig. 3). It has been established that the wear of ceramic cutting plates is due to periodic microchipping (separation and removal of grain conglomerates) in the surface layers of their contact areas with a gradual change of the relief. As a rule, microstresses control similar processes [7]. In this process the physical and chemical phenomena are closely related and mutually supportive, and they intensify one another.

Studies of the reasons for chipping of ceramic cutting plates have established that failure is distinctly brittle. The character of the failure of a ceramic cutting plate depends on the stresses which have been produced, while technological defects, which are stress concentrators, initiate failure. The character and probability of the failure of ceramic tools are affected by the geometric parameters of the tools, the properties of the ceramic, and the form and regime of mechanical working. Under the same stress conditions tools fabricated

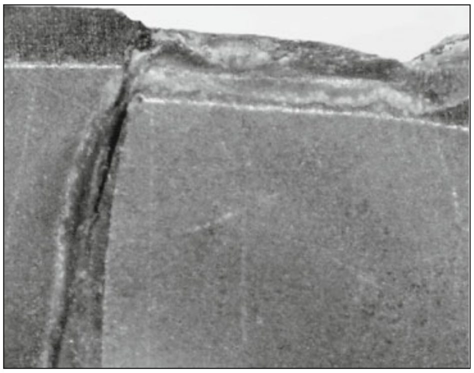

Fig. 4. Character of the failure of a VOK71 ceramic cutting plate during machining of a blank made of ShKh15 steel (cutting velocity $v = 90$ m/min, feed rate $S = 0.075$ mm/rev, cutting depth $t = 0.35$ min).

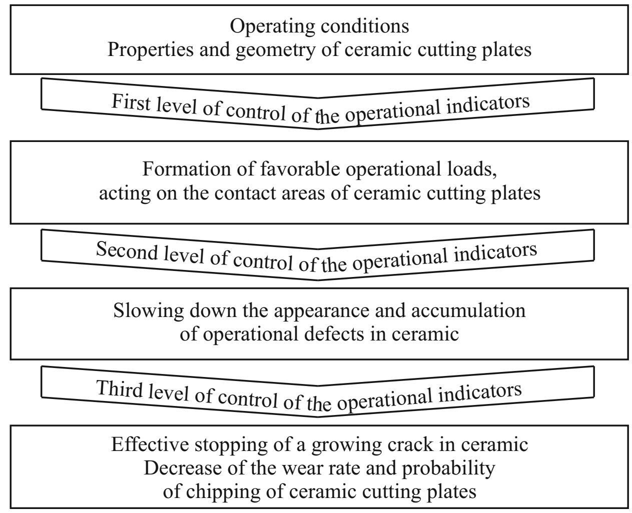

Fig. 5. Algorithm for controlling the operational indicators of ceramic cutting plates.

from ceramic with higher ultimate bending strength σ_b, stress intensity factor K_{1c}, and thermal stability T_f have greater serviceability.

An important feature of the wear and failure of ceramic cutting plates is the appearance of defects in the form of discontinuities in regions of high local stresses. These defects have been found in the surface layers of ceramic tools (in what follows, operational defects, since the nature of their origin is determined by the operational loads). Operational defects are nucleation sources for cracks, whose development results in the separation of grains (grain conglomerates) and their removal from the surface layer of the cutting plates. It has been established that the regions of appearance and accumulation of operational defects are determined by the level of the microstresses formed in the surface layer of the cutting plates (or in the component of the ceramic) under operational loads.

As a rule, these defects appear initially at the location where several large grains butt together in the region with the highest microstresses. The appearance of these operational defects increases the local stresses, which initiates the process of their accumulation. The accumulation of operational defects signifies the onset of nucleation of “operational” cracks. The size of these cracks is comparable to that of grains, and these cracks “weaken” the ceramic, decreasing its Young’s modulus and ultimate strength.

After cracks form they develop from the region with the highest concentration of operational microdefects along the trajectory of high local stresses. For a crack in the interior volume of a cutting plate a necessary condition for the crack to reach the surface is a continuous system of high microstresses. The development of operational cracks in direct proximity to the surface results in separation of a “particle of wear” from the surface of ceramic tools or microchips on their contact areas. If a crack aperture lies deeper, the stable stage of crack development converts into a stage of rapid and unstable growth, which ultimately results in a macrochip on the tool or complete failure of the tool as a result of merging of such cracks into a mainline crack. The character of the development of these cracks, which result in failure of ceramic cutting plates, is shown in Fig. 4.

The possibility of controlling the performance indicators of ceramic cutting tools was determined using the mechanisms found for the wear and failure of such tools. The control algorithm is divided into three levels, each of which has a different effect on the performance indicators of ceramic cutting plates (Fig. 5). An important element of the algorithm is the supposition according to which ceramic cuttings tools must be developed for prescribed operating conditions.

At the first control level the ceramic acts on contact processes mainly through its thermophysical properties. Because these properties are changed purposefully it becomes possible to decrease the force and thermal loads on ceramic tools.

At the second level the properties and structure of the ceramic completely control the thermal and stress states, created by external loads, of the ceramic cutting plates. Micro- and macrostresses are formed in ceramic cutting plates under an external load. The density and elastic modulus as well as the Poisson ratio, linear thermal expansion coefficient, thermal conductivity, and specific heat capacity have the greatest effect on the formation of macrostresses. At the same time the main structural components of the ceramic produce their own microstress fields, which also affect the overall stress state of the cutting plates. The degree of this influence is determined by the ratio of the densities, elastic moduli, and linear thermal expansion coefficients as well as the Poisson ratio, thermal conductivity, and specific heat capacity of the main structural components of the ceramic. An unfavorable combination of these properties will result in the appearance of regions of high local stresses in the cutting plates. The structure of the ceramic is an important factor, determining the particulars of wear and failure processes in ceramic cutting plates.

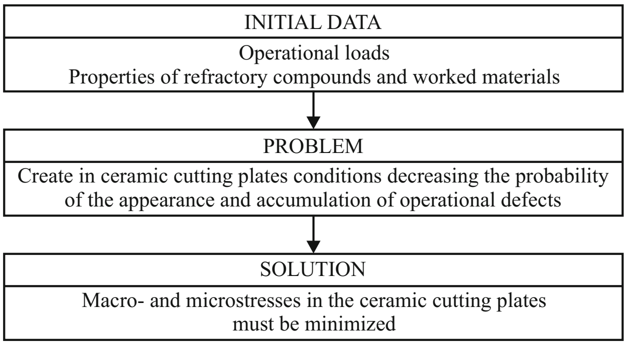

Fig. 6. Schematic diagram of the mechanism for controlling the operational indicators of ceramic tools at the second level.

At the third level, “wear – fracture,” the capability of ceramic to stop growing cracks has the greatest effect on the operational indicators of ceramic tools in the thermal and stressed states formed in them. The appearance of barriers on the trajectory of steadily growing cracks results in braking, branching, or stopping of the cracks [8]. The barrier creation mechanism for cracks developing in brittle materials has been adequately understood and is widely used in the development of tool ceramic. This mechanism is effectuated by forming a structure of the type “matrix – hardening phase” in the ceramic material.

The effectiveness of the barriers for developing cracks depends on the character and level of the external loads. For the some loading conditions these barriers are effective, which signifies braking and a possibility of complete stopping of crack development crack. In other cases a barrier does not fulfill its purpose and does not brake a crack, as a result of which the ceramic cutting plate fractures. This is due to the action of extremely high operation loads on the plates.

In this connection, for ceramic tools it is necessary to actuate the higher, second level of control of the operational indicators of the tools. A schematic diagram of this control mechanism is presented in Fig. 6. It is proposed that conditions be created such that the minimal levels of the micro- and macrostresses are produced in “loaded” cutting plates because of a deliberate choice of the components of the ceramic and coating.

This mechanism acts to decrease the probability of the appearance of operational defects, preventing c rack nucleation and increasing the defect-free operating time. Ultimately, the wear rate and chipping probability for ceramic tools should decrease. The practical implementation of this mechanism for controlling the operational indicators of ceramic cutting plates is based on the condition that their stressed state can be controlled.

The most effective variant of controlling the operational indicators of ceramic tools is the first level, which is geared toward creating favorable loading conditions during high-speed cutting. For example, it has been established that deposition of a coating on ceramic cutting plates makes it possible to control simultaneously their surface properties and the contact processes during cutting, including heat fluxes. In practice, this approach can be implemented even now by means of coatings obtained using the plasma of a vacuum-arc discharge [9]. A method in which beams of accelerated particles pulverize and activate the surface of a ceramic has been proposed for obtaining high-quality coatings on oxide-carbide ceramic plates. These coatings make it possible to increase the stability of ceramic tools by up to a factor of 3 compared with the initial tool.

The development and improvement of technologies which effectively implement these mechanisms of controlling the operational indicators of tools with ceramic cutting plates should determine the main trends in their development. It should be noted that their implementation in practice will be possible only on the basis of coordinated actions taken by specialists in allied spheres of science and engineering.

CONCLUSIONS

The trends in the future development of ceramic cutting plates have been determined by analyzing the prospects for and problems of using tools with such plates in modern metal working.

The scientific-research and experimental-design work performed at the Moscow State Technological University “Stankin” is focused on the practical implementation of an algorithm developed to control the operational indicators of ceramic cutting plates. This algorithm is geared toward creating ceramic cutting plates for prescribed operating conditions using a method developed to design them and technologies for controlling the properties of their surface layer.

The solution of these problems will make it possible to encourage commercial enterprises to make wider use of tools with ceramic cutting plates in modern metal working.

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